Tunable Elliptical Split Ring Resonator Using Single Varactor Diode for filter applications

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Abstract

The scope of this paper is to examine the effect of changing the structure of split ring resonator SRR from circular to an elliptical shape. The theoretical analysis of circular SRR (CSRR) is first examined and its results are compared with the simulated ones. Comparison between both configurations is also introduced. The new elliptical SRR (ESRR) can be adapted to operate in a multi-range of frequencies. The effect of gap position in ESRR resonant is also examined. When both gaps are moved but still aligned, the resonant frequency still the same. But when single gap is moved only the resonant frequency in changed to reach its maximum value when both gaps are in the same position. Frequency tunability can be offered by loading only a single varactor diode between the ESRR's metallic rings. The resonant frequency of the ESRR can be controlled by varying the capacitance of the varactor diode. Finite Element Method FEM is used to simulate the proposed structures using Ansys HFSS. A prototype of band notched coplanar waveguide filter loaded with single reconfigurable ESRR is fabricated and measured. A 0.5 pF single capacitor element is used instead of using varactor diode and the measured S_{21} is compared with the simulated results. Very good agreement has been obtained between them. A 5.6 GHz and 5.4 GHz notch frequencies in the filter operating frequencies are obtained using ESRR without and with varactor loading, which covers WLAN band.

Keywords: Metamaterials; CPW filter; band notch; Circular SRR; elliptical SRR; frequency tuning; Varactor diode; FEM; HFSS.

1. Introduction

A new type of fabricated structures or composite materials with non-natural electromagnetic (EM) properties were introduced in the microwave and optics fields. These new types of materials are known as metamaterials [1]. SRRs are one of new artificial material that exhibits unusual properties. SRRs are of special significance as they can be easily integrated with planar antennas to get highly directional beam patterns because of their enhanced negative refractive index material (NRIM) properties [2]. The SRR is constructed from two open metallic rings, spaced with suitable distance. SRR could be formed with different configuration like; circular SRR (CSRR) [3], square SRR (SSRR) [4], hexagonal SRR (HSRR) [5], elliptical SRR (ESRR) [6-7]. An electromotive force appears around the SRR due to external magnetic field applying along the z-axis and the coupling between the two rings induces the current from one ring to the other ring through a distributed capacitance formed due to the inter ring spacing [8].

In comparison to CSRR, ESRR have many advantages. In ESRR, there are two controlling parameters ring radius and radii ratio. Also the ESRR has smaller area for the same resonant frequency. In CSRR, rotating the gap position keeps the distance between them constant and this not the case in ESRR. ESRR is introduced previously in [6] without any detailed parametric study to evaluate its performance or its controlling parameters. Also it is introduced in [7] with its equivalent circuit model and mathematical analysis but in millimeter frequency range.

Recently, there have been high demands on designing band stop filter using Split Ring Resonator (SRR) compared to other resonator [8-9]. A planar compact band stop filter using circular SRR is proposed in [8]. In [9] a square SRR array is designed for a 5.8 GHz band-stop filter.

Reconfigurable SRR could be used in multiband applications. There have been several studies on tunable or reconfigurable SRR by introducing two or more PIN diodes as switches or varactor diodes as a variable capacitors [10-19]. Using many PIN or varactor diodes complicates the manufacturing process by the need of DC biasing.

In this paper, the structure of CSRR is changed to ESRR by decreasing its major to minor radii ratio. The effect of this change is recorded. Also, the gap position rotation effect is examined to record its influence on the resonant frequency. Both gaps are first rotated, while both are still aligned, then one of them is only moved. A single varactor diode is loaded between the ESRR metallic rings to achieve tunable ESRR.

To validate the proposed ESRR structure with and with the varactor diode, it is used to notch a frequency band in coplanar waveguide CPW filter. A single ESRR instead of two SRRs [20] is loaded in the backside of CPW filter. A prototype of the proposed filter design is fabricated and its characteristics is measured. Very good agreement between simulated and measured results has been obtained.

A single varactor diode, instead of four varactor diodes as in [16], is loaded between the two ESRRs metallic strips near one of its gaps. This facilitate the structure and reduces the fabrication error. Also it reduces the needed connections to deliver each varactor diode its needed DC voltage. A single 0.5 pF capacitor element is used instead of using varactor diode which is not available in our laboratory and the measured S_{21} is compared with the simulated results. Very good agreement has been obtained between them. A 5.6 GHz and 5.4 GHz notch frequencies in the filter operating frequencies are obtained using ESRR without and with varactor loading, which covers WLAN band [21].

2. Theoretical Analysis

Figure 1 shows a schematic view of a CSRR formed with metallic strips of width, c, and radii r_a and r_{ext} forming the inner and outer rings, respectively with inter ring spacing, d. The splits on the inner and outer rings have gap dimensions g_1 and g_2, respectively, lying diametrically opposite on the same axis. The structure is printed on a dielectric substrate with dielectric constant, ε_r and thickness h. The equivalent circuit model of these split ring resonators is shown in Fig. 2, [22]. Under the exposure of the external magnetic field, the induced electromotive force around the SRR causes a current which passes from one ring to the other through the inter ring spacing, d and the structure behaves as an oscillatory L-C circuit.

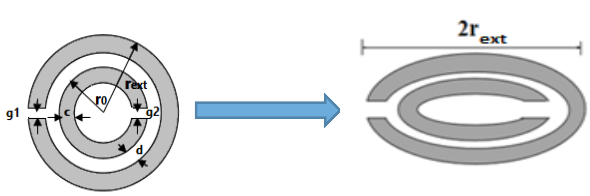


Figure 1: Circular to elliptical split ring resonator.

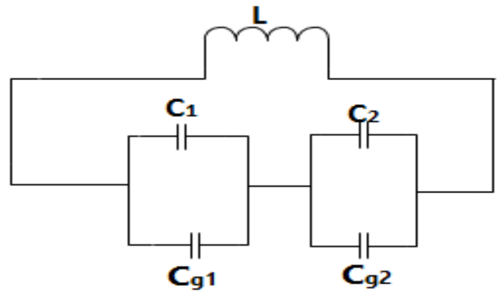


Figure 2: Equivalent circuit model of the CSRR

The expression of the resonant frequency of different circular SRR [23] is given as

$$f_{oc} = \frac{1}{2\pi\sqrt{LC_{eq}}} = \frac{1}{2\pi\sqrt{L_T\left[\frac{(\pi r_o - g)C_{pul}}{2} + \frac{\varepsilon_o ct}{2g}\right]}} \qquad (1)$$

Where L_T is the total inductance of the SRR and C_{eq} is the equivalent capacitance of the structure, c and t are the width and thickness of the metallic strips, respectively and ε_0 is the free space permittivity. And C_{pul} is the capacitance per unit length. Finite element method (FEM) in the frequency domain is used to simulate the proposed structures using Ansys HFSS [24].

3. Results and discussions

3.1 Circular SRR

The resonance frequency for CSRR is computed using Eq. (1). The CSRR is printed on a duroid dielectric substrate having ε_r = 2.2 and thickness h =1.6 mm. The computed values calculated using Eq. (1) are compared with the simulated ones and are presented in Table 1. Table 1 shows the effect of variation of CSRR parameters, for the same value of r. When the ring width c increases, the resonant frequency also increases. When r_{ext}=2mm and C increased from 0.4 to 0.5 mm the resonant frequency increases from 8.78 to 9.28 GHz. The resonant frequency decreases with increasing in r_{ext} value.

Table 1: Comparison of computed and simulated resonance frequencies of CSRR for different cases for d=0.25mm, g_1=g_2=0.2mm

SRR dimensions (mm)			resonant frequency (GHz)	
	r_{ext}	C	Computed	simulated
Case 1	2	*0.4*	*8.78*	*8.2*
Case 2		*0.5*	*9.28*	*8.9*
Case 3	2.5	*0.3*	*6.2*	*5.54*
Case 4		*0.5*	*6.71*	*6*
Case 5	3	*0.4*	*5.05*	*4.59*
Case6		*0.5*	*5.2*	*4.8*
Case 7	3.5	*0.4*	*4.14*	*3.62*
Case 8		*0.5*	*4.25*	*3.74*

3.2 Elliptical SRR

In comparison with CSRR, ESRR has two design parameters which are major radius and minor to major radii ratio. These parameters facilitate the resonant frequency adjustment. A geometrical reshaping of circular to elliptical s SRR is done by varying the ratio between the minor to the major axis (r_a), the other dimensions have the same symbols, as shown in Fig. 1. At r_a=1 this means that it is a CSRR. By decreasing r_a values, it's converted to ESRR and the resonant frequency also increased. This effect of changing the ratio on the resonant frequency is shown in Fig. 3. Figure 3 shows that the resonant frequency changed from 4.8 to 6.2 GHz when r_a changed from

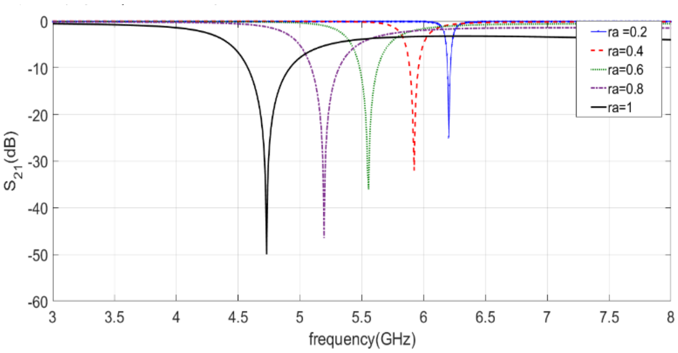


Figure 3: Simulated S_{21} of the ESRR for r_{ext}=3mm, for different r_a values

Also ESRR has less area compared to CSRR for the same resonant frequency. For example, the ESRR with r_{ext}=3mm, c=0.5mm and r_a=0.4 resonates at 6 GHz which can be obtained by CSRR with r_{ext}=2.5mm and c=0.5mm, as shown from Table 1 and Fig. 3.

3.3 ESRR gap rotation effect

The effect of varying the gap position on the transmission parameter is examined in this section. Another Priority of ESRR is that, the distance between two gaps depends on gap position which may affect the resonant frequency. The gap position is changed by changing its skew rotational angles θ_1, and θ_2 as shown in Fig. 4. As shown in Fig. 5, the resonant frequency almost the same, when both gaps have the same skew angles. By changing θ_1 with θ_2 =0, the resonant frequency increased to reach to its maximum value at 7.8 GHz as shown in Fig. 5. By varying θ_2 with θ_1 =0 the resonant frequency increased to reach the same maximum value as shown in Fig. 5.

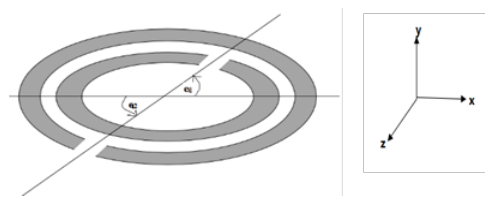


Figure 4: the gap skew rotation angles θ_1, θ_2

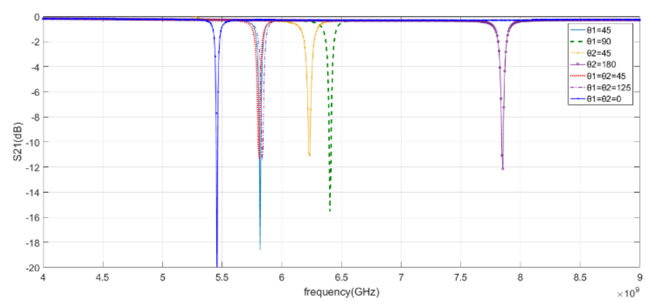
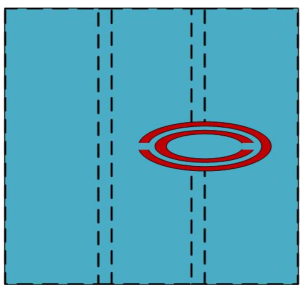


Figure 5: Gaps' skew angle effect for r_{ext}=3.5mm.

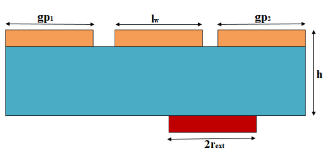
3.4 Coplanar waveguide filter loaded by reconfigurable ESRR

To examine the proposed ESRR simulation results, a single ESRR is loaded in the back side of CPW filter to notch a certain frequency band. A prototype of the CPW filter loaded by single ESRR is designed as shown in Fig. 6. The coplanar waveguide is printed on dielectric substrates having ε_r = 2.2 and thickness h =1.6 mm. The CPW having ground plan widths (gp_1 = gp_2= 7mm) and the strip line width (L_w =6mm) with a slot width of 0.2 mm that yielding a characteristic impedance of 50 Ω. By loading CPW with single ESRR with dimensions c =0.5mm, d =0.25mm, g_1=g_2=0.2mm, r_{ext}=3mm a notch frequency 5.67GHz can be obtained. A single varactor diode, instead of four varactor diodes, is loaded between the two ESRR metallic strips near one of its gaps. Varactor diode capacitance can be controlled by varying its applied reverse DC voltage. The varactor position is also optimized. Skyworks SMV2019-040LF varactor diode characteristics is used to simulate the proposed structure. Varactor diode capacitance can be varied from 0.3 pF to 2 pF. The effect of capacitance variation on the resonant frequency is shown in Fig. 7.

We find that the notch frequency decreases with the increase in the value of the capacitance .when the capacitance value is 0.3 pF the notch frequency will be 5.57 GHz and when the capacitance value is 0.9 pF the notch frequency will be 5.1 GHz which cover WLAN band.



(a)



(b)

Figure 6: Schematic view of (a) elliptical SRR placed symmetrically on the back side of the coplanar waveguide and loaded with varactor diode (b) Cross-sectional view of CPW backed by ESRR.

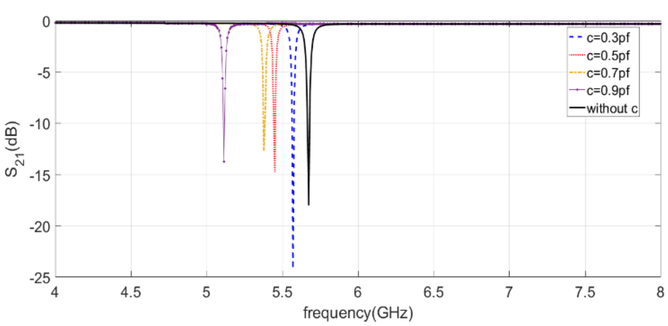
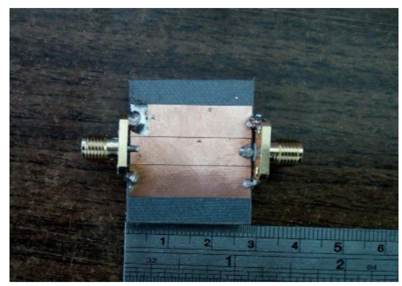


Figure 7: Simulated S_{21} characteristics of the proposed reconfigurable ESRR

3.5 Measured Results and Discussions

A prototype of the proposed coplanar waveguide loaded with ESRR is fabricated and the S_{21} is measured in Electronics Research Institute in Cairo, Egypt. Figure 8 shows the photograph of the fabricated antenna. A single capacitor element is used instead of varactor diode which in not available in our laboratory. Figure 9 shows the comparison between measured and simulated S_{21} results. Very good agreement has been obtained between them. The discrepancy is mainly due to the fabrication tolerance and hand welding inaccuracy. A 5.6 GHz and 5.4 GHz notch frequencies in the filter operating frequencies are obtained using ESRR without and with varactor loading, which covers WLAN band.



(a)

(b)

Figure 8: Photograph of the fabricated coplanar waveguide loaded with reconfigurable ESRR. (a) Top. (b) Bottom

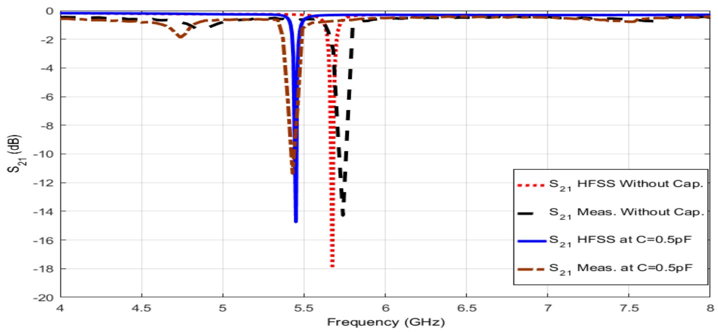


Figure 9: HFSS Simulated and measured S_{21} of the proposed coplanar waveguide.

4. Conclusion

Circular to an elliptical geometrical reshaping of split ring resonator SRR is presented and tested. The new ESRR can be designed to operate in a multi range of frequencies. The effect of gap skew rotation angles in ESRR characteristics is also examined. When the ESRR gaps are aligned regardless, their skew angles the resonant frequency almost the same. When one of the two gaps is rotated only, the resonant frequency is also changed to reach its maximum value when both gaps in the same position. Frequency tunability of ESRR can be achieved by using varactor diodes. Instead of Four varactor diodes, a single one is loaded near one of the ESRR gaps. The resonant frequency of the SRR can be tuned and controlled by varying the capacitance of the varactor diode. Finite element method (FEM) in the frequency domain is used to simulate the proposed structures using Ansys HFSS. A prototype of band notched coplanar waveguide filter loaded with single reconfigurable ESRR is fabricated and measured. A 0.5 pF single capacitor element is used instead of using varactor diode and the measured S_{21} is compared with the simulated results. Very good agreement has been obtained between them. A 5.6 GHz and 5.4 GHz notch frequencies in the filter operating frequencies are obtained using ESRR without and with varactor loading, which covers WLAN band.

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